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EARLY MISSIONS TO COMETS

By

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Introduction

Approximately 20 years ago, Biermann proposed that the direction and motion of the plasma tails of comets are due to momentum transfer from a continuously flowing stream of solar particles known as the solar wind. This interpretation was based on the observations that such gas tails trailed behind the anti-solar direction by a measurable amount, several degrees, and that detailed structures visible in the tail were observed to move in the anti-solar direction with relatively high velocity and with irregular accelerations. Thus, the study of the interaction of the solar wind with comets was begun and as such must be reckoned as the first quantitative prediction of the solar wind.

Subsequently, ten years later direct in-situ observations of the magnetized solar wind began with satellites carrying instruments into interplanetary space. Since then, extensive experimental and theoretical studies of the solar wind and its interaction with the earth, moon and the planets have been conducted. These results demonstrate the significant energy input by the solar wind to the upper regions of planetary atmospheres and/or its magnetosphere via both direct momentum transfer and wave particle interactions. More recently, after another 10 year interval, dramatic observations of vast atmospheres of atomic hydrogen, measured in the resonance line of hydrogen alpha, were performed on Comets Tago-Sato-Kosaka (1969g) and Bennett (1969i). In the case of Comet Bennett, the scale size of the atmosphere exceeds 10^7 km

and confirmed the developing views that earlier production rates of cometary gases was underestimated by several orders of magnitude. Thus our present view of the solar wind interaction with comets includes not only the well known feature of ion tails but also a vast hydrogen atmosphere which must interact strongly with the solar wind and thus create a much larger target for direct spacecraft investigations than previously anticipated. It is the purpose of this brief report to suggest two specific early missions to the Comets Grigg-Skjellerup in 1977 and Encke in 1980 as precursor missions to more ambitious missions to Encke rendezvous in 1984 and Halley intercept in 1986.

Mission Guidelines

One of the primary constraints guiding these studies has been the desire to use existing spacecraft designs for four reasons.

1. High confidence of success and demonstrated ability to support the class of experiments conceived as appropriate for these missions,
2. Low cost of implementation since no spacecraft design or development work would be required and hence financial feasibility is considerably higher than were the opposite true,
3. Flight schedule should be administratively realistic from the viewpoint of mission definition, experiment selection, Congressional approval and instrumentation delivery and
4. Spacecraft system should have a scientific heritage in which studies of the solar wind, interplanetary dust and other particulate

matter, and interactions of the solar wind with different objects was a principal objective, to assure compatibility between experiments and spacecraft.

From the scientific viewpoint the principal objectives were:

1. Precursor missions to determine in situ the gaseous composition, both neutral and ionized, and the nature of the solar wind interaction with the cometary gases,
2. Target comets should appear during the five year interval 1977 to 1982, sufficiently in advance of Halley's 1986 apparition so that feedback from results so obtained would be possible,
3. Sufficiently well-known trajectory so that launch could occur prior to recovery and not require extensive maneuvering by the spacecraft and lastly,
4. The flythrough velocity should be less than 15 km/sec in order to permit utilization of existing instrumentation for the study of the composition and the interactions without significant distortion due to a higher relative velocity.

With these guidelines, the existing stable of interplanetary spacecraft was surveyed and the comet appearances in the time interval sieved to determine a fortuitous conjunction of intrinsic spacecraft capability with cometary apparition. This search was fruitful in identifying several such opportunities of which the two best missions are herein summarized: It should be stressed here that the spacecraft

structure, power system, telemetry system, configuration and launch vehicle which are considered for these two missions are not simply paper conceptions of what might be done.

The spacecraft IMP is a series of earth (and moon) orbiting spacecraft, which beginning in 1963 definitively studied the interplanetary magnetic field and solar wind, the collisionless bow shock surrounding the earth associated with the supersonic solar wind interaction with the geomagnetic field and the existence of the geomagnetic tail. It has already demonstrated its low cost in earlier missions and as such is a spacecraft designed for operation at 1 AU supporting accurate measurements of magnetic fields and low energy plasma and particle fluxes since great care is exercised in the design and fabrication of a magnetically RFI clean spacecraft. The HELIOS spacecraft, considered for the 1980 Encke mission, is a solar probe designed to operate at 0.25 AU and also provide a magnetically and RFI clean laboratory bench from which detailed measurements of the solar wind and its composition can be studied. The first HELIOS spacecraft will be launched in 1974 and the second in 1975.

Minimum modifications to these spacecraft are required for the cometary mission targets anticipated. Of course, important modifications will be in the area of the experiment repertoire in which additional experiments related to cometary studies will be added replacing other experiments. Secondly, the high gain antenna utilized on HELIOS will also be utilized on the IMP spacecraft in order to provide for adequate

telemetry transmission during its cometary intercept. Detailed studies have been underway for some time to confirm and document the present status of these missions.

Mission Objectives

As earlier remarked, the primary objectives of these missions is to study the nature of the solar wind interaction with the comets, the composition of the gaseous cometary atmosphere and possibly the details of the aft body portion of cometary phenomena, the ion and dust tails. Final targeting of the spacecraft flythrough trajectory will be accomplished in conjunction with the experimenters finally selected for flight. Here we only state the overall scientific objectives and representative experiments to be performed.

Figure 1 illustrates the scale size of the interaction region between the solar wind and the comet. It is expected that a collisionless shock wave will develop as the super Alfvénic solar wind interacts with the cometary atmosphere. This may be similar to the observed bow shock which surrounds the earth, Venus and Mars (most recently identified in the USSR results from Mars 3). The distance to this shock front is estimated to be 10^6 to 10^7 km.

Behind the shock is expected a region of subsonic magnetohydrodynamic turbulence similar to that of the earth's magnetosheath. Here thermalized solar wind plasma is deviated around the comet along a surface identified as an MHD discontinuity, a contact surface. Only

direct in-situ measurements will be able to establish the existence and the positions of these surfaces, which are important to understand the fundamental nature of the interaction between the ionized gas of the solar wind and the ionized or neutral gases of the cometary atmosphere. An intercept trajectory with a spacecraft carrying instrumentation to measure magnetic fields, plasmas, neutral and ionized gases, and fluctuating magnetic and electric fields will definitively establish both the nature and the position of the discontinuity surfaces and the separate plasma-field regimes thus created.

In addition, as the spacecraft flythrough trajectory penetrates further towards the cometary nucleus, the study of emissions and particulate matter in the nucleus of comets becomes feasible. In fact, it is necessary to consider the hazard of damage to the spacecraft and/or instruments from particulate matter in selecting a final impact parameter (the radius of closest approach to the nucleus) in order to avoid damaging the spacecraft. Depending upon which comet one is studying, one may then also have an opportunity to perform measurements in the tailward region of the interaction region and possibly to establish whether or not the stylized variations of cometary tail structures are associated with an imbedded magnetic field entrapped from the interplanetary medium, are related to waves along the contact surface or finally structures imbedded within the multiple neutral sheets which may exist in the cometary tails analogous to the neutral sheet of the earth's magnetic tail.

As knowledge of the solar wind interaction with the earth's magnetic field has increased, we have come to appreciate more closely the parallel which may exist between the geomagnetic tail and cometary ion tails. However, only in-situ observations of ion tails will permit a determination of the completeness of such an analogy.

For the measurement of the composition of the ions and gases, various instruments to perform spectrometric studies are required. Some of these will be direct measurements of mass per unit charge or energy/unit charge while others will be of the indirect radiation types in which the emission characteristics of the ions and molecules will be utilized for observations unobscured by the earth's atmosphere and/or night glow.

Mission Analysis

The search for interesting flythrough missions in the 1977 - 1982 time period quickly led to two outstanding targets, Grigg-Skjellerup in 1977 and Encke in 1980. Both of these opportunities have certain advantages that markedly distinguish them from previous proposals for comet-intercept missions. This distinction is due not only to the favorable orbital geometry for these apparitions, but also to some unusual extended-mission possibilities associated with them. Descriptions of both the primary and extended phases of these missions are given below.

1977 Grigg- Skjellerup Mission: Grigg-Skjellerup is a typical short-period comet that was discovered in 1902 and next seen in 1922. It has been observed at every apparition since then ($T \sim 5$ years), the last time in 1972 when it presented a sharp nucleus and a fan-shaped coma. It does not seem to possess a tail. The orbit of Grigg-Skjellerup is depicted in Fig. 2 where it can be seen that the perihelion passage and the ecliptic crossing, which are almost coincident, will occur very close to the earth in 1977 (at about 0.20 AU). Despite a large perturbation by Jupiter in 1964, its present orbit is well known as evidenced by the fact that its predicted perihelion date for the 1972 apparition was within 0.01 days of the observed time. Furthermore, the nongravitational forces affecting the motion of this comet are extremely small, and are in fact an order of magnitude smaller than many other short-period comets (e.g., D'Arrest).

Previous studies of comet-intercept missions have stated that the orbits of comets are not known well enough to consider a launch before the comet is recovered and a better orbit is determined. While this may be true in some cases, the indicated a priori orbital accuracy for Grigg-Skjellerup justifies a pre-recovery launch. In any event, the chances for the earliest recovery yet recorded for Grigg-Skjellerup are quite good in 1977. If it postulated that recovery will occur when the comet attains a nuclear magnitude of 18, the recovery date would be about December 1, 1976, which is more than four months before intercept.

The nominal mission profile is summarized in Fig. 3. Because of the moderately high inclination of the comet's orbit (21.10°), the planned intercept point is located in the ecliptic plane. With this specification the launch energy requirement (C_3) is quite low. In fact, $C_3 < 3 \text{ km}^2/\text{sec}^2$ for a two-week launch window. Conditions at the cometary encounter are almost ideal. The relative velocity is only 15.2 km/sec, and the angle between the relative velocity vector and the spacecraft spin axis is 24.6° . This angle, which is termed the relative aspect, is an important parameter for considering those experiments measuring the composition of the cometary coma. The small value of the relative aspect is rather fortuitous because antenna-pointing constraints require that the spacecraft spin axis should be normal to the ecliptic plane.

Another feature of the cometary encounter worthy of mention is that the comet will be close to its maximum brightness, having a total magnitude of 9.98. At this time, dark-sky conditions for the sighting of Grigg-Skjellerup will exist for about two hours at a 35°N latitude earth-observatory site and about five hours at a 35°S latitude site. These conditions are adequate for obtaining good earth-based spectroscopic measurements at the encounter which should be useful in correlating the spacecraft measurements.

In Fig. 3A it can be seen that the spacecraft is placed into a trajectory that not only intercepts the comet, but also returns to the earth. The purpose of this extended-mission strategy is to carry out particle and field investigations of previously unexplored regions of the earth's magnetosphere, especially in the geomagnetic tail between 80 and 500 earth radii. Due to the high degree of commonality of the scientific instrumentation for many of the cometary and magnetosphere experiments, the earth-return extended mission mode is very attractive.

Although there is only one trajectory that returns to the vicinity of the earth when the comet intercept date is fixed and transfers that are longer than one year are not allowed, it is possible to open the launch window to about two weeks by adding a modest velocity correction (< 150 mps) after the cometary encounter. When the spacecraft returns to earth, a small solid retro-motor is used to brake it into a high-apogee earth orbit. As shown in Fig. 3B, the spacecraft eventually enters the geomagnetic tail and spends about four months in the area near the sun-earth L_2 libration point. According to the Gylden-Moulton hypothesis, the gegenschein may be caused by dust particles temporarily trapped in this region. In-situ analysis using the cometary solid particle detectors could settle this issue.

The mission just described could be performed with a slightly-modified version of a current Explorer spacecraft (IMP-H/J). The principal changes to this spacecraft, which is spin-stabilized, would be

the addition of a hydrazine propulsion system and a high-gain antenna. A sketch of the cometary Explorer spacecraft is shown in Fig. 4. Total spacecraft weight would be about 950 lb. which includes 150 lb. of experiments, 200 lb. of hydrazine fuel, and a 75-lb. solid retro-motor. Because of the small launch energy requirements, the 950-lb. spacecraft could be launched by the comparatively inexpensive Delta-2914 launch vehicle.

1980 Encke Mission: Of all the short-period comets, Encke passes closest to the sun (0.34 AU) has the shortest orbital period ($T \sim 3.3$ years), and is probably the most interesting from a scientific viewpoint. It has also received the most attention in terms of its prior observation and orbit analysis. Discovered in 1786, it has only been missed at one apparition (1944) since 1819. The physical appearance of Encke depends on the solar activity, with the formation of a central condensation and a tail quite likely when the sun is most active. It is worth noting that the 1980 return will take place only one year beyond the time of maximum solar activity. The diameter of Encke's coma is around 10^5 km, and the length of the tail is somewhat less than 10^6 km.

As can be deduced from Fig. 2, the earth-comet sighting geometry is excellent during Encke's 1980 passage. It is estimated that the comet will be recovered near the latter part of July in 1980, which is about a month before the scheduled launch date. Since Encke's orbit is very well known, there does not appear to be any guidance problem that cannot be managed by the spacecraft's on-board propulsion system.

The nominal mission profile is outlined in Fig. 5. To obtain a low relative velocity and also fly through the comet when it is very bright, it was decided to aim for an intercept in the vicinity of Encke's perihelion. Note that the earth will be in an excellent position to observe the perihelion encounter. The exceptionally favorable alignment of the earth and Encke in 1980 permits the spacecraft to follow a transfer trajectory that is located in essentially the same plane as Encke's orbit. This technique has apparently been overlooked in previous investigations where it has been erroneously stated that the minimum achievable relative velocity for a 1980 intercept of Encke is about 23 km/sec. Even though the extremely low relative velocity of 7.13 km/sec can only be obtained with an "on-time" launch, a launch 12 days earlier would yield a relative velocity of 10 km/sec and the launch energy requirement would actually decrease to $C_3 = 87.5 \text{ km}^2/\text{sec}^2$.

The HELIOS spacecraft (illustrated in Fig. 6) would be a "natural" for an Encke intercept at 0.34 AU. This spin-stabilized spacecraft is designed to operate at solar distances as low as 0.25 AU, and the only major modification that would be required for the Encke mission would be the addition of a hydrazine propulsion system. With this modification, the total spacecraft weight would be approximately 950 lb. including 150 lb. of experiments. This payload is well within the capability of the Titan IIID/Centaur launch vehicle which can deliver almost 1400 lb. when $C_3 = 100 \text{ km}^2/\text{sec}^2$.

In the post-encounter mission phase the spacecraft could be used to carry out further investigations of the interplanetary medium within the earth's orbit augmenting the HELIOS A/B data that will be obtained during a period of minimum solar activity. However, there is another extended-mission goal that should receive some consideration, that is to try for a second intercept of Encke in 1984. This possibility exists because the spacecraft's orbital period is almost exactly equal to one-sixth Encke's period. Therefore, if a 3 1/2-year spacecraft lifetime could be achieved, two separate flythroughs of Encke would be possible, one near solar maximum in 1980 and the other near solar minimum in 1984.

Concluding Remarks

This brief paper has discussed two specific missions for early precursor missions to the Comets Grigg-Skjellerup in 1977 and Encke in 1980, which will provide definitive in-situ observations of the interaction of the solar wind with the cometary atmosphere and the composition of the neutral and ionized gases forming the atmosphere surrounding the nucleus. No attempt will be made to directly sample the nucleus itself but rather the entire environment of a comet and its energetics associated with the solar wind will be investigated.

Subsequently, it is proposed that follow-on missions include a rendezvous with Encke in 1984, based upon the observational results obtained in 1980 and finally an intercept with the dramatically visible target Halley in 1986. We have rejected consideration of a rendezvous

with Halley for several reasons among which is the extremely long-lived mission required to achieve such an objective with presently conceived (but not now available) launch systems. A progressive, orderly study of comets is essential to full utilization of mission opportunities for such "expensive" targets as Encke rendezvous and Halley intercept.

Acknowledgment

We are pleased to acknowledge the collaboration of our GSFC colleagues, Drs. B. Donn, L. Burlaga, W. Jackson, and K. Ogilvie in the informal discussions regarding these precursor missions. We are also indebted to F. Mann and G. Wyatt for their assistance with the trajectory analysis, and to D. McCarthy and J. Dezio for their contribution to the spacecraft design.

References

1. Biermann, L., Comets and their Interaction with the Solar Wind, Quarterly Journal, Royal Astronomical Society, Vol. 12, 1971, pp. 417 - 432.
2. Friedlander, A. L., Niehoff, J. C., and Waters, J. I., Trajectory Requirements for Comet Rendezvous, Journal of Spacecraft and Rockets, Vol. 8, No. 8, August 1971, pp. 858 - 866.
3. O'Dell, C. R., and Roberts, D. L., eds., Proceedings of the Cometary Science Working Group, Yerkes Observatory, Williams Bay, Wisconsin, June 1971.

Figure Captions

1. Plasma Flow Near to a Comet (Biermann, 1971)
2. Orbits of Comets Grigg-Skjellerup and Encke (Ecliptic Plane Projections)
3. Nominal Mission Profile for 1977 Grigg-Skjellerup Opportunity. (Spacecraft Trajectory is shown with respect to the Sun-Earth Line in the Ecliptic Plane).
 - 3A. Heliocentric Phase
 - 3B. Geocentric Phase
4. Cometary Explorer Spacecraft
5. Nominal Mission Profile for 1980 Encke Opportunity
6. HELIOS Spacecraft

BOW SHOCK AND CONTACT SURFACE

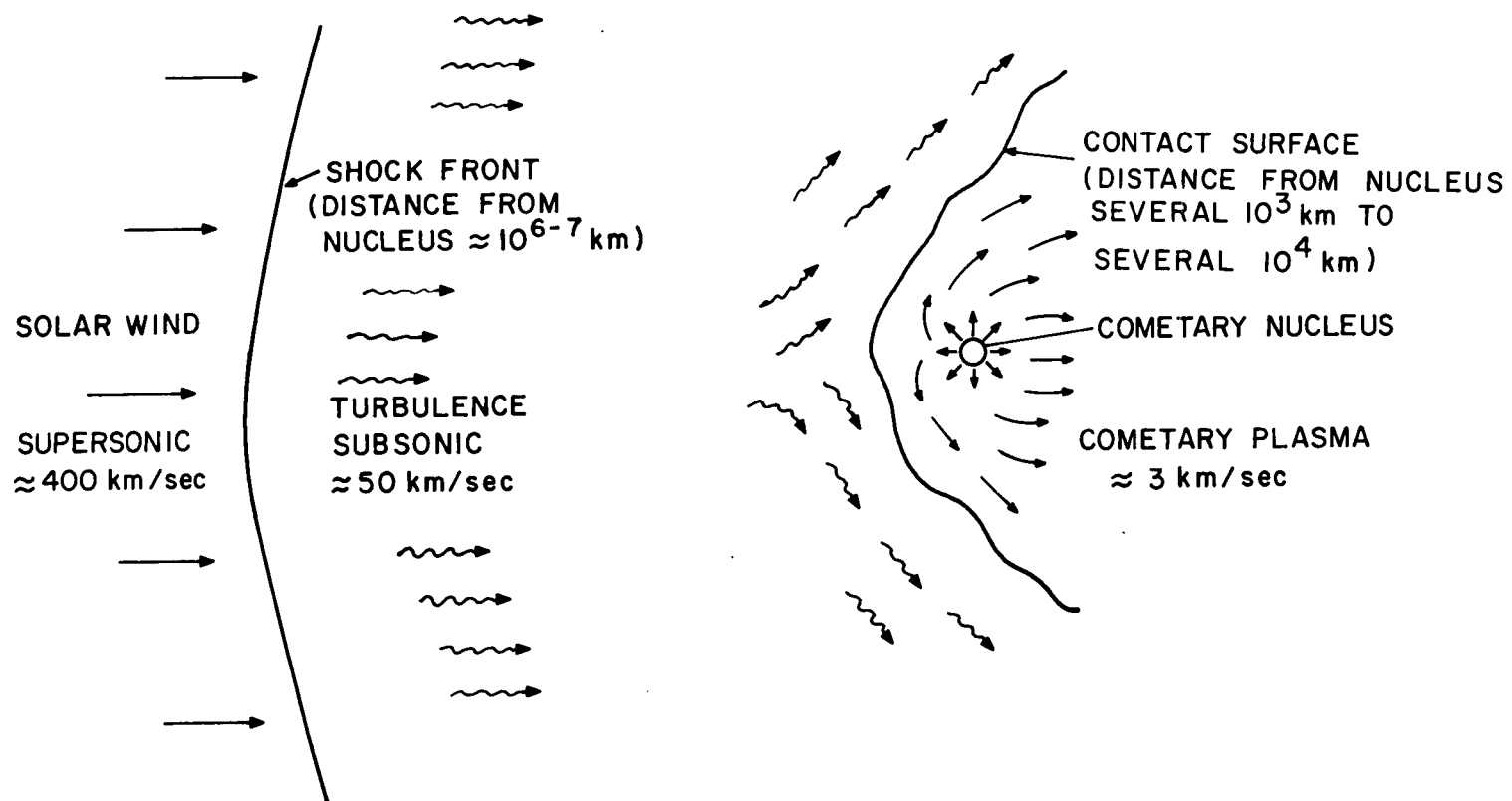
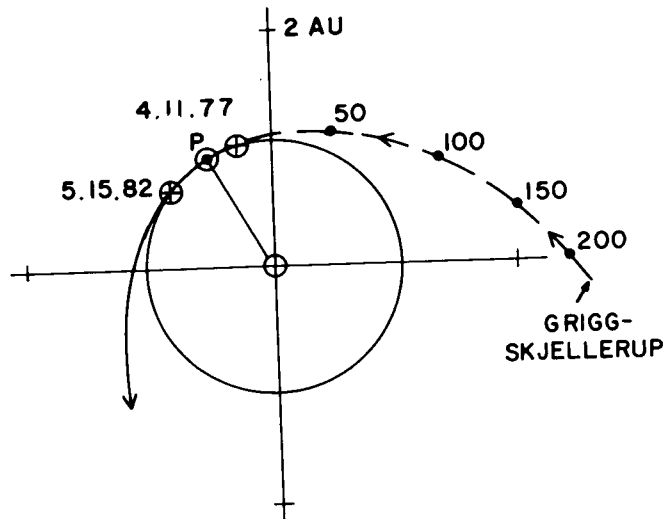


FIGURE 1

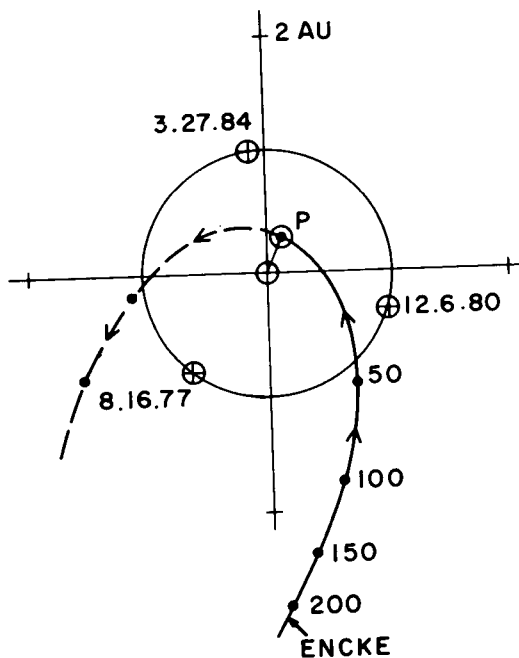
GRIGG - SKJELLERUP

PERIHELION = 0.993 AU
 APHELION = 4.932 AU
 ECCENTRICITY = 0.665
 INCLINATION = 21.10°
 PERIOD = 5.099 YEARS



ENCKE

PERIHELION = 0.340 AU
 APHELION = 4.097 AU
 ECCENTRICITY = 0.847
 INCLINATION = 11.95°
 PERIOD = 3.304 YEARS



— ABOVE ECLIPTIC
 - - - BELOW ECLIPTIC

- COMET AT STATED NUMBER OF DAYS BEFORE OR AFTER PERIHELION
- ⊙ COMET AT PERIHELION AND ECLIPTIC INTERSECTION
- ⊕ EARTH AT TIME OF COMET'S PERIHELION

FIGURE 2

18

LAUNCH

NOV. 4, 1976

$$C_3 = 2.37 \text{ Km}^2/\text{sec}^2$$

COMET INTERCEPT APRIL 11, 1977

EARTH DISTANCE = 0.20 AU

RELATIVE VELOCITY = 15.2 Km/sec

RELATIVE ASPECT = 24.6°

EARTH RETURN

OCT. 26, 1977

RETRO ΔV = 206 mps

PERIGEE = 14,000 Km

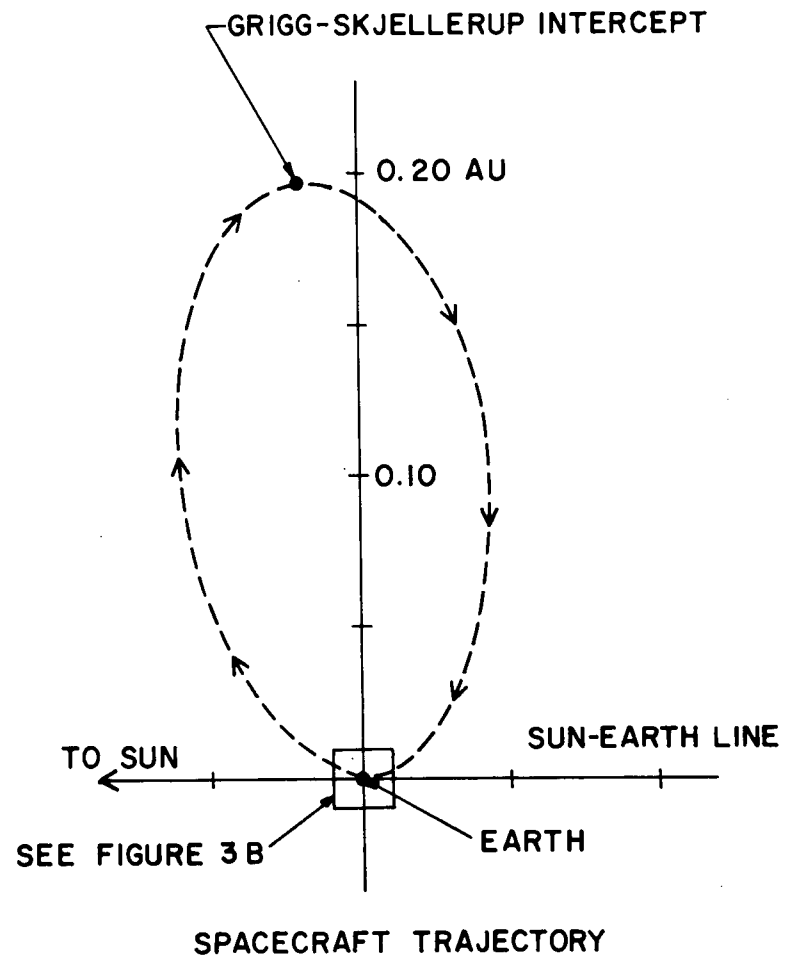


FIGURE 3A

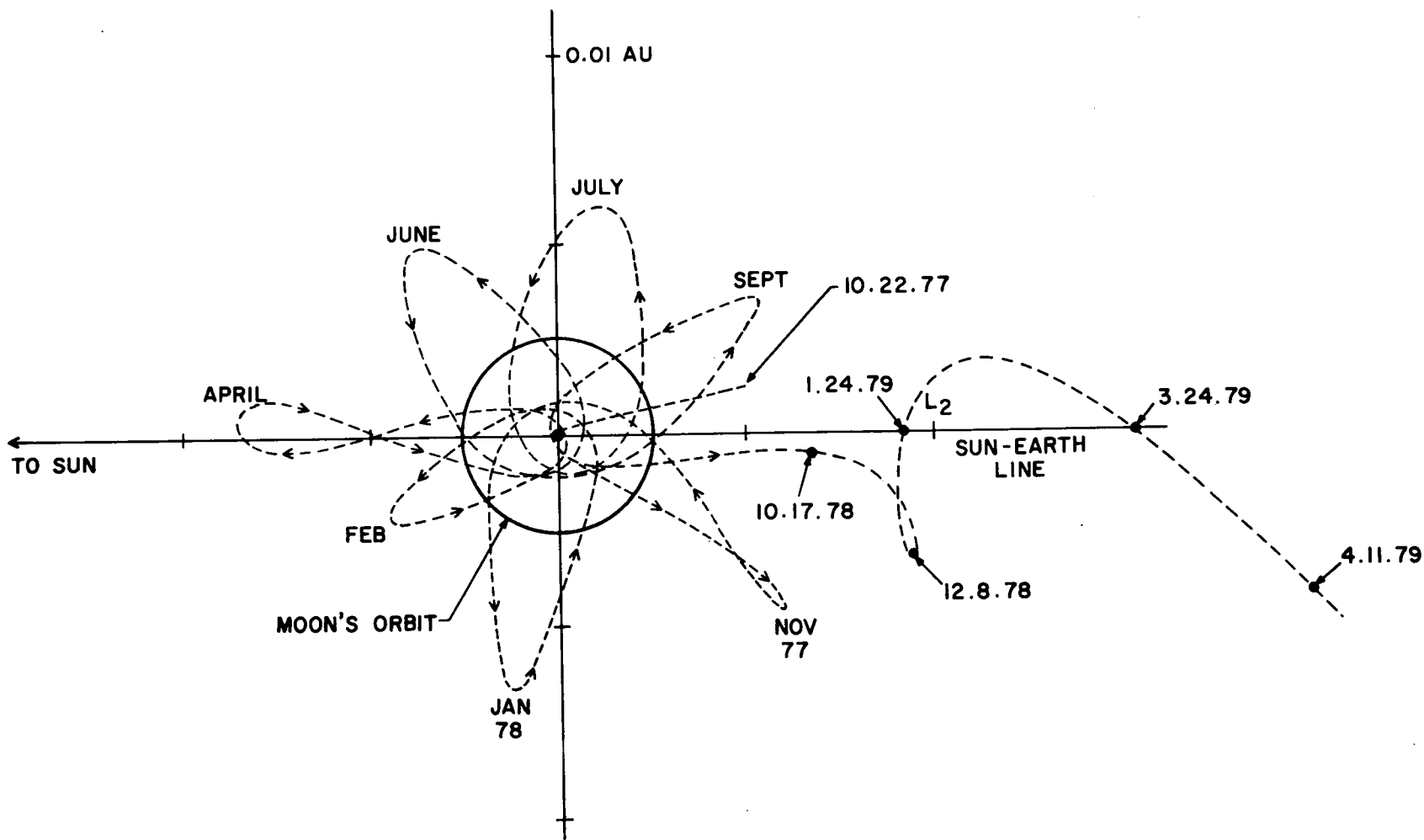


FIGURE 3B

COMETARY EXPLORER

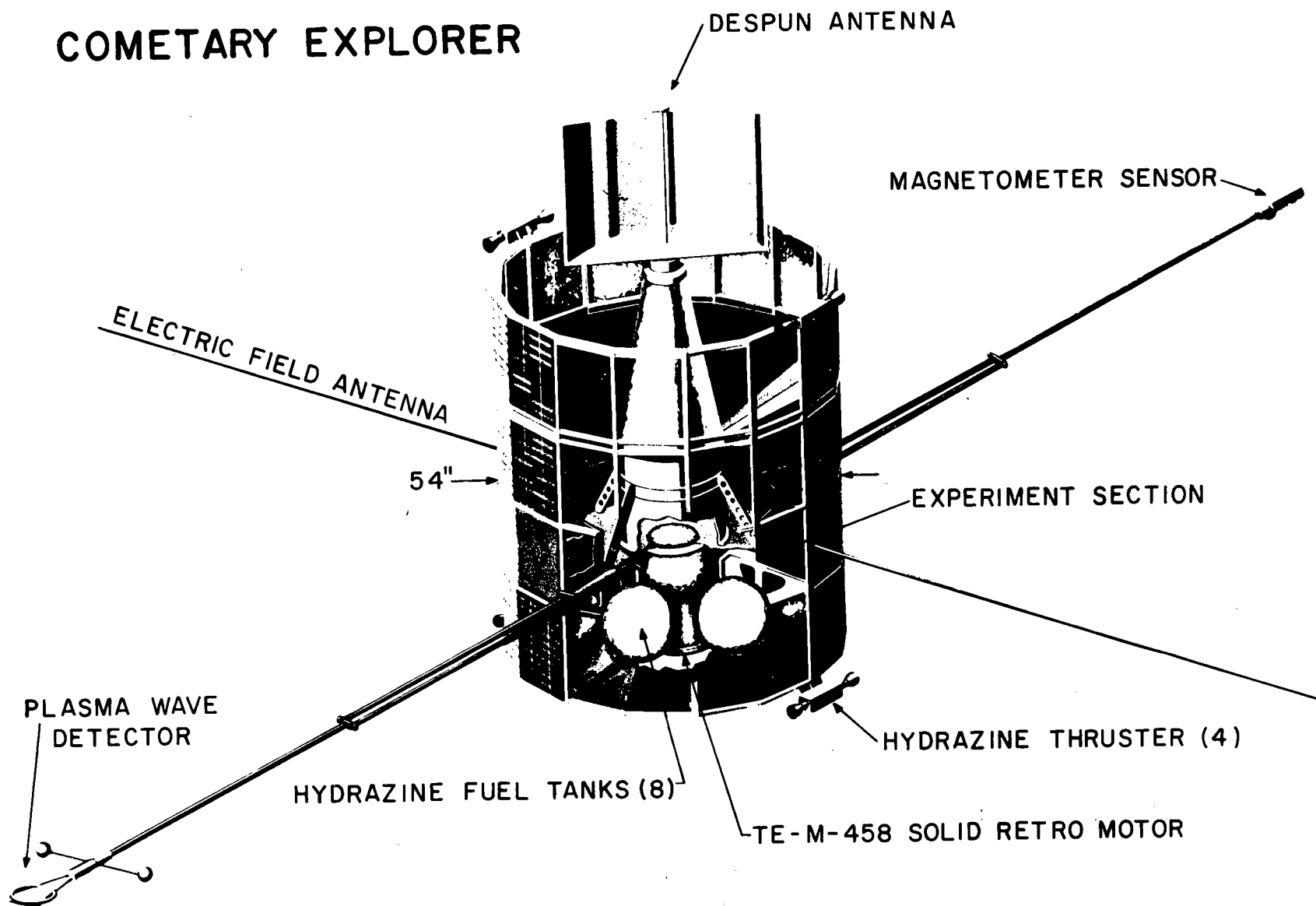


FIGURE 4

LAUNCH

AUG. 27, 1980

$C_3 = 100 \text{ Km}^2/\text{sec}^2$

COMET INTERCEPT

DEC. 7, 1980

EARTH DISTANCE = 1.03 AU

RELATIVE VELOCITY = 7.13 Km/sec

RELATIVE ASPECT = 77°

SPACECRAFT TRANSFER ORBIT

PERIHELION = 0.34 AU

APHELION = 1.01 AU

ECCENTRICITY = 0.50

INCLINATION = 12.11°

PERIOD = 0.553 YEARS

ORBIT PROJECTIONS IN
ECLIPTIC PLANE

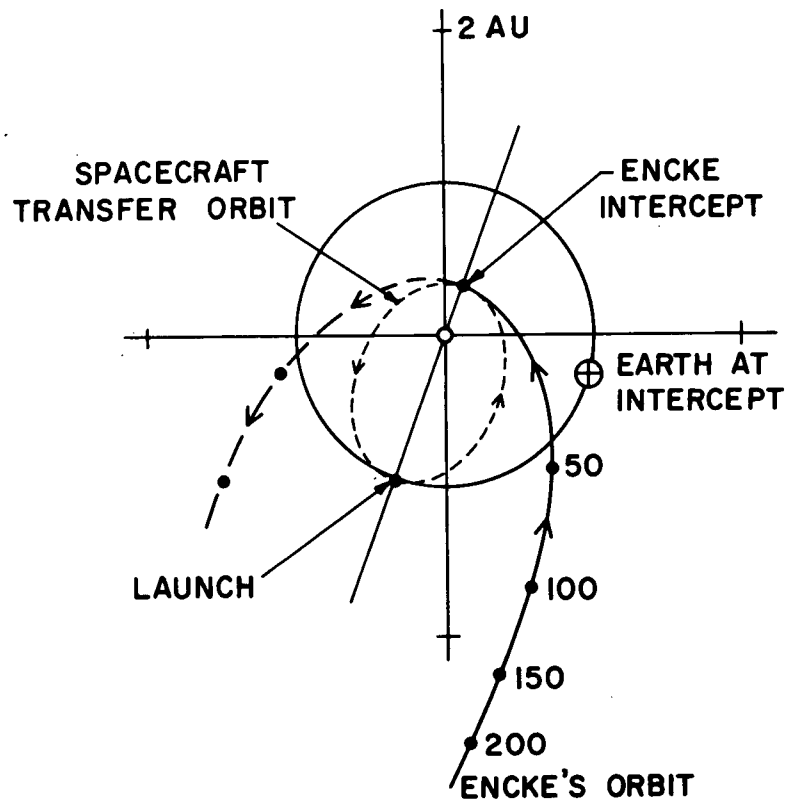


FIGURE 5

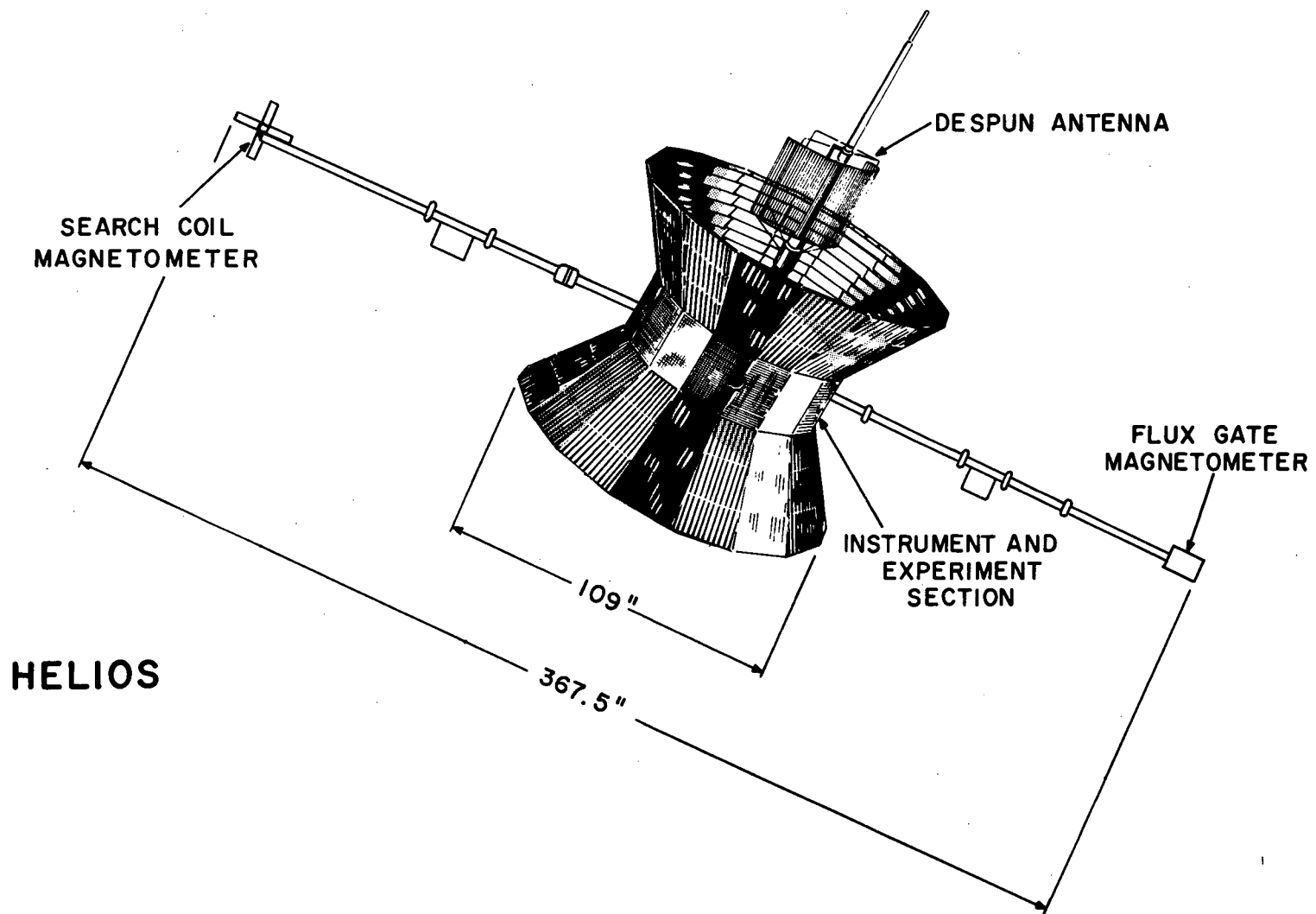


FIGURE 6